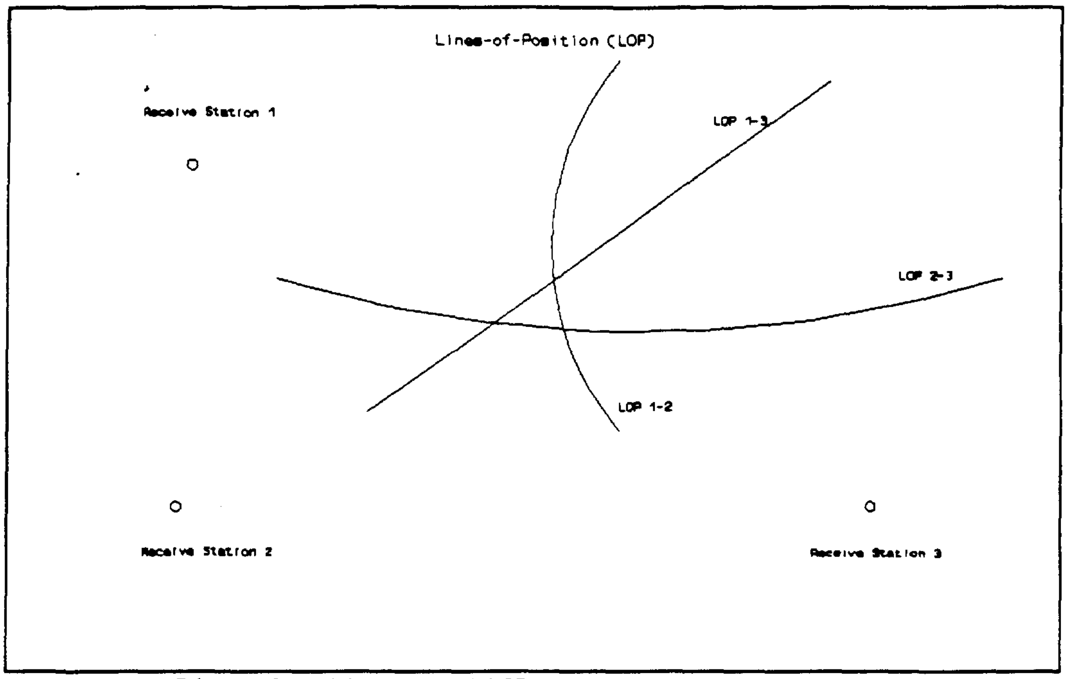

Figure 2 Lines-of-position in an LMS system

an interfering signal transmitted from a point near a vehicle would interfere in a roughly equal fashion with the reception at all four receive sites. In contrast, an interferer located close to one receive site would degrade or perhaps completely destroy the time-of-arrival measurement at that site, but would have less impact on the measurements at other sites. However, if there are only four receive sites serving a particular area, then the loss of one of those four sites destroys the system's ability to generate location estimates in that area.

The performance of any time-difference-of-arrival pulse-ranging system is limited by geometry. The phenomenon is called "geometric dilution of precision" (GDOP). Roughly put, it means that, all other things being equal, the farther the actual location is from the center of region served by the receivers, the greater the location error because the lines-of-position become more nearly parallel. As this happens, small errors in time measurement translate into large errors in estimated locations. Figure 3, Figure 4 illustrates the magnification of errors through GDOP.[8]

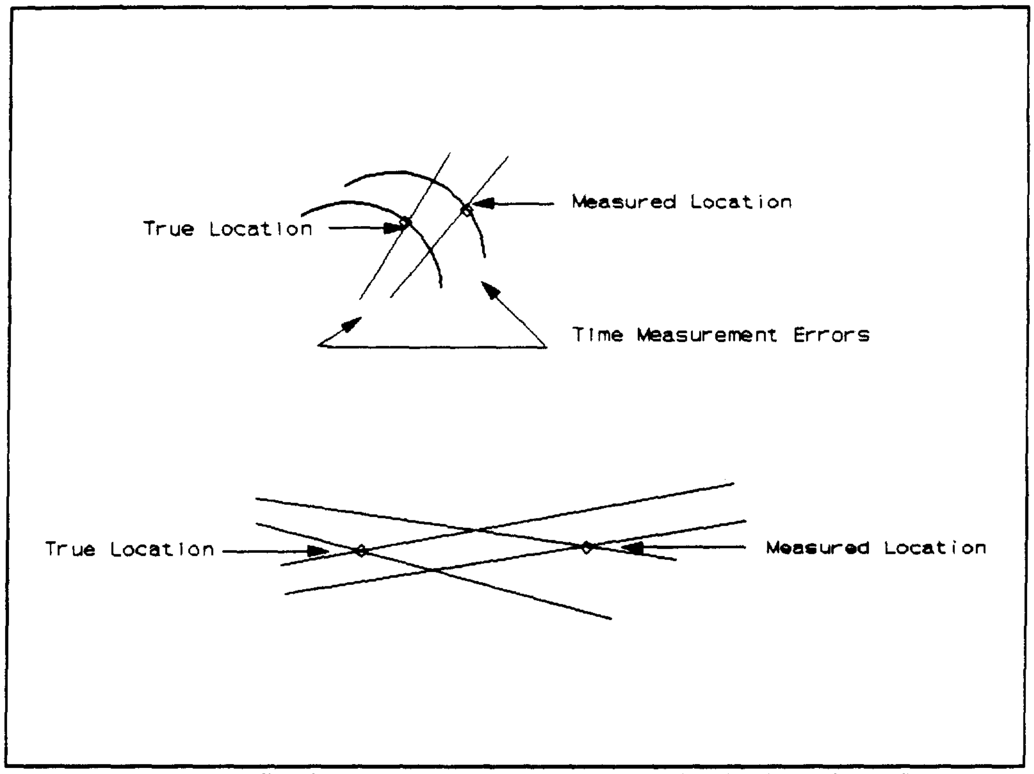

Figure 3 Magnification of errors through geometric dilution of precision

IV. The Noise Environment for Pulse-Ranging Systems

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[8] Mathematically, GDOP is defined as the ratio of the variance of the location estimate divided by the variance of the time measurements properly scaled by the speed-of-light. As such, the technical definition of GDOP takes into account effects of position on received signal strength as well as on the orientation of the lines-of-position. In practical cases, the GDOP grows rapidly as the position to be located moves away from the served region and the lines-of-position become nearly parallel.

Pulse-ranging systems are authorized by the FCC to operate in two 8 MHz bands (904-912 MHz and 918-926 MHz). These bands are shared with industrial, scientific and medical equipment (ISM), government systems, radio amateurs, and unlicensed Part 15 devices.

The thermal noise is -105 dBmW[9]. In reality the noise in most practical receivers will actually be greater because the circuitry of the receiver adds additional noise.

Given the presence of radars, ISM equipment, amateurs, and Part 15 devices in the band, the observed noise at receive locations is much higher than the thermal noise floor. Measurements show that the noise-like signal levels seen in the wideband pulse-ranging segments of the LMS band typically fall in the range of -95 to -85 dBmW[10]. Thus, existing operations in the band have raised the noise floor by 10 to 20 dB above the levels that would ordinarily be associated with thermal noise. Adjacent bands do not show such noise levels[11].

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[9] In the absence of any interference, the thermal noise associated with a receiver is normally given by ***kTB*** where ***k*** is Boltzmann's constant (k = 1.38 x 10^{-23} J/K (W/Hz/K) or -198.6 dBmW per Hz per degree Kelvin.), **T** is the temperature in degrees Kelvin, and **B** is the bandwidth. For land mobile systems at 900 MHz the unavoidable noise is the thermal noise generated by the ground, trees, buildings, etc. "seen" by the antenna.

[10] See "Theoretical and Field Performance of Radiolocation Systems", Teletrac Report, June 25, 1993 (Section 3.1 and Table 1).

[11] For example, the FCC requires that the noise figure of UHF TV receivers not exceed 14 dB (47 CFR 15.117(g)) when tuned to channel 69 (800-806 MHz). Such a requirement would be pointless if the ambient noise and interference in that band were as high as is observed in the LMS wideband segments. Similarly, firms market antenna preamplifiers for use in both UHF TV and 800/900 MHz land-mobile radio. Such devices would be of very limited use if those bands had the noise and interference power observed in the LMS wideband pulse-ranging segments.

We can also calculate the added power that would come from a cochannel LMS station. If we assume a 500-watt EIRP transmitter, an operating frequency of 908 MHz, three dBi gain at the receive antenna, separation of ten miles, and free space propagation, then the received power would be -56 dBmW![12] Because this level is 30 to 40 dB greater than the existing noise power today, a typical five watt mobile transmitter would have to be replaced by a transmitter of 5,000 to 50,000 watts to overcome the interference. If the separation were only one mile, a likely event in an urban area,[13] the interfering power would be a further 20 dB higher or -36 dBmW for a total increase of 50 to 60 dB over the current noise and interference levels and an increase of 69 dB over the thermal noise floor. Now the mobile transmitter has to operate at 500,000 to 5 million watts to overcome the interference.

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[12] These are all quite reasonable assumptions for calculating the interference generated by the fixed station of one LMS system into a fixed station of another. Pinpoint proposes to operate its fixed stations at 484 W EIRP. Teletrac operates fixed

The worst case is even more severe. It is quite plausible that an LMS station could be located within 100 yards of another LMS base station. With stations this close together, the interfering signal rises to -16 dBmW — almost 90 dB above the noise floor.

These interference levels can also be compared to everyday occurrences. Consider ordinary speech. Conversation in an average office is easy. But, relaxed conversation next to a blaring radio (about 30 to 40 dB louder) is impossible although one can shout to make oneself heard. Carrying on a conversation next to a small aircraft engine (55 dB louder than conversational level) is impossible.[14]

To conclude, it is clear that a cochannel LMS system substantially increases the noise and interference affecting the performance of an LMS system. And by substantially we mean several orders of magnitude — an enormous increase in interfering energy. As we will see later, existing and proposed LMS systems are engineered to operate well in today's noise environment and, although these designs can accommodate some increase in noise and interference, they would not be able to cope with interference at these high levels.

V. Interference to Wideband Pulse-Ranging Systems

There are a variety of interference scenarios. A few practical examples are set below.

The least harmful type of interference involves a low-power interfering transmission from a transmitter on the ground and placed close to a pulse-ranging system's base station.

[14] The relative strength of different sound levels is based on Table 8 (page 40-9) of **Reference Data For Engineers: Radio, Electronics, Computer, and Communications**, Eighth Edition, 1993, M. E. Van Valkenburg editor.

The added energy from the interfering transmission[15] decreases the accuracy of the estimation of the time-of-arrival of pulses only at that receiver. This affected time-of-arrival measurement is then fed to the network control center, along with time-of-arrival measurements from other sites, resulting in a degraded location estimate. If the interfering signal is sufficiently strong at the receiver, then it prevents the receiver from detecting a presence of the pulse, thereby eliminating the affected base station from the network. However, interference will have rendered the base station essentially useless before this point.

A more severe type of interference occurs when the interfering transmitter operates using a high antenna that permits a line-of-sight path for the interfering transmission to systems in the hierarchy of use, transmit a powerful pulse for a short period and then remain silent for a much longer period.[16] LMS systems can be engineered to work around such interfering signals.

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[16] The primary government radar used in the 902-928 MHz band is a long-range two-dimensional air surveillance radar manufactured by Raytheon and used by the Navy. The Navy radar emits 300 kilowatts of output power from a klystron power source. The radar antenna has a 28 dBi gain, with a 3.3 degree horizontal beamwidth and a 9 degree vertical beamwidth. The Navy radar scans 360 degrees horizontally at a scan rate of 6 RPM or 12 RPM. The occupied bandwidth of the emitted signal is 1 MHz at -3 dB. The signal consists of a 2 microsecond pulse followed by a linear frequency sweep across 1 MHz in 125 microseconds. The pulse pair is repeated 285 times per second.

This Navy radar is used on approximately 200 to 300 Navy ships located offshore and in Navy shipyards. Some of the locations where Navy radar systems are commonly used include Southern California, Hawaii, Norfolk, and Puerto Rico.

VI. Comparing Pulse-Ranging Systems With Communication Systems

Location systems differ from communications systems in fundamental ways. Instincts honed on data communications systems can lead to wrong conclusions when one analyzes the effect of interference on wideband pulse-ranging systems.

For example, a location system must use multiple fixed receivers to process a single pulse, while communications systems can function with a single receive point. Similarly, the primary benefit of direct sequence spread-spectrum in communication systems is to provide protection against noise and multipath, while the primary benefit of direct sequence techniques in location systems is to provide for a high pulse power and high bandwidth without requiring high peak power.

In data communications the key criteria are bit error rate (primarily a function of signal-to-noise ratio) and data rate (primarily a function of bandwidth). In location systems the key issues are accuracy and capacity (both complicated functions of bandwidth, number of receive sites, receive site location, and signal-to-noise ratio). Each time-of-arrival measurement provides many bits of information. The objective is acceptable accuracy in a reasonable measurement time. Unless one takes into account the different objectives of these two quite different types of systems, it is easy to mislead oneself in the analysis of these systems. One must be careful not to apply concepts from data communications uncritically to analogous issues in the analysis of pulse-ranging LMS systems.

VII. Consequences of Interference to Pulse-Ranging Systems

Two quite distinct types of information can be extracted from signals received in a radio wave. First, a data sequence or an analog waveform modulated onto a radio frequency carrier at the transmitting site can be demodulated by the receiver. With digital transmissions, the receiver detects the individual symbols or sequences of symbols transmitted. Noise, interference, propagation disturbances, and other statistical anomalies on the radio channel require the receiver to determine whether a zero or a one was transmitted (hypothesis testing).[17]

Second, receivers measure various parameters of radio signals such as signal strength and the time-of-arrival (TOA). Time-of-arrival measurement permits distance to be determined using the known velocity of light. This is the basis of radar and of position determination using multilateration to fix the unknown location of a transceiver. Time-of-arrival measurement in the presence of noise, interference, and other statistical anomalies on the radio channel requires the receiver to perform an estimation function. The measure of performance now is accuracy rather than bit error rate.[18]

In data communications we are looking for data transport at low bit error rate. In location systems we are measuring time-of-arrival. These are quite different tasks.

A. Loss of Accuracy in Position Measurement

Because a radio channel always contains noise and interference, the measurement of the time-of-arrival of a pulse will rarely yield the true time-of-arrival. Rather, the measured value will be a random variable related to the true time-of-arrival. The tools of modern statistics can be used to make useful inferences about the accuracy of these corrupted measurements and about the accuracy of quantities calculated from these measurements.

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[17] The usual measure of performance is the probability of symbol error — bit error rate (BER) — if binary symbols are transmitted. There is a vast literature on the design of optimal receiver processing to accomplish this.

[18] Intuitively, the accuracy of time-of-arrival measurement is proportional to the sharpness or steepness of the leading edge of the pulse which, in turn, is proportional to the reciprocal of the signal bandwidth.

In the discussion that follows, we first develop an approximate derivation of the limits on time-of-arrival measurement and then we present the Cramér-Rao bound — a fundamental limit on measuring time-of-arrival — which tells the best we can do for such measurements in the presence of noise.

To illustrate simply how errors in time-of-arrival measurement result from noise and interference, consider the transmission of a pulse with rise time, t_r and amplitude A. Then the location of the measured time-of-arrival of the pulse leading edge will be disturbed by noise with power N as follows:

$$\frac{\sqrt{N}}{\sigma_t} = \frac{A}{t_r} \qquad \textbf{Eqn. (1)}$$

where

σ_t is the r.m.s. time-of-arrival error, and
$\sqrt{N}$ is the r.m.s. noise voltage.

Equation (1) is a rough estimate and is simply an application of similar triangles. Figure 3 illustrates the error process. The ratio of the amplitude error (noise voltage) to the timing error is the same as the amplitude of the entire pulse to the rise time of the pulse.

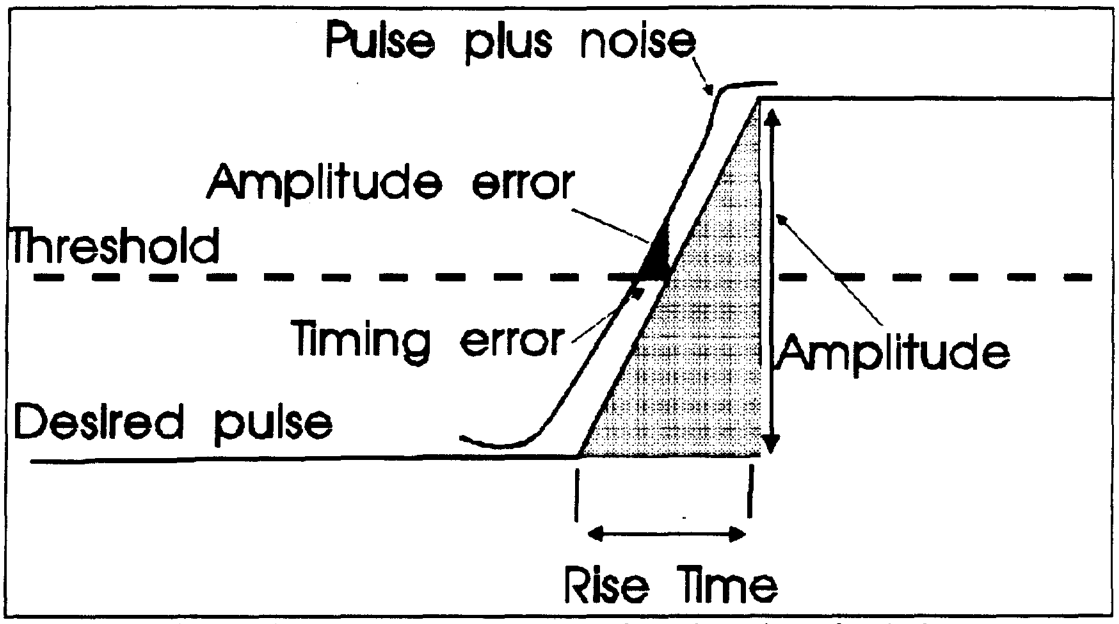

Figure 4 Noise distorting the measurement of a pulse's time-of-arrival

This simple equality is consistent with the Cramér-Rao (C-R) lower bound on <u>any</u> estimate of time-of-arrival. That is, one can do no better regardless of the measurement signal processing.

Building on Equation 1, we get:

$$\sigma_t^2 \propto \frac{1}{(SNR)B^2} \quad , \qquad \text{Eqn. (2)}$$

where we have taken

SNR = signal-to-noise ratio = $\frac{A^2}{N}$,

and the bandwidth, B is

$$B \propto \frac{1}{t_r} \quad .$$

What is the best we can do in measuring time-of-arrival? One answer to this question is given by the Cramér-Rao bound, which sets lower limits on the average error of <u>any</u> estimator.[19]

[19] The Cramér-Rao bound is a powerful technique well known in statistics where it can be applied to most practical statistical estimation problems. The Cramér-Rao bound on measuring the time-of-arrival of a pulse is useful in the analysis of radar systems and is commonly presented in radar system textbooks, see, for example, Skolnik, **Introduction to Radar Systems**, Second Edition, McGraw-Hill, p. 405. We do not derive the Cramér-Rao bound here but we note that it is presented in several references (e.g., **Reference Data for Engineers**, Eighth Edition, p. 36-19, or D. J. Torrieri, "Statistical Theory of Passive Location System," IEEE Transactions on Aerospace and Electronic Systems, Vol. AES-12, No. 2, March, 1978). We use a slightly modified form of the bound, combining noise and signal power in the SNR term and accounting for the difference between chip duration and pulse duration. The derivation of the form above from the textbook form is straightforward.

can also be magnified by the geometry. The general relationship between the errors, the differential distance measurements and the transmitter position accuracy is described by a set of parameters known as the Geometric Dilution of Position (GDOP)[23]. We earlier presented an intuitive discussion of GDOP. For a detailed discussion of GDOP see Spilker[24] or Torrieri.[25]

C. Examination of tradeoffs implied by the Cramér-Rao Bound

A system designer creating an LMS system seeks to meet four economic goals:

- low-cost mobile units,
- low operating costs,
- accuracy that meets customer needs, and
- high system availability.

The Cramér-Rao bound provides an excellent tool for understanding the tradeoffs forced on any LMS service provider operating in the presence of interference. Higher signal-to-noise ratio can be achieved by increasing the power transmitted by the mobile unit. But, increasing power increases the cost of the mobile unit. Similarly, additional receive sites can combat interference, but at the expense of higher operating costs. Similarly, accuracy can be traded off against interference protection or system capacity.

We note that the LMS system built by Teletrac operates, albeit with some implementation loss, near the limits predicted by the Cramér-Rao bound. The form of the performance tradeoffs observed in the Teletrac system are consistent with the

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[23] GDOP is defined as the ratio of the r.m.s. position error to the r.m.s. ranging error.

[24] J.J. Spilker, J., *Fundamentals and Optimization of GPS User Systems*, forthcoming, 1993, in particular section 4.

[25] Op. cit.

Cramér-Rao bound. The Cramér-Rao bound states a binding limit on the practical engineering of LMS systems.

Examining the Cramér-Rao bound allows us to identify other tradeoffs. In particular the Cramér-Rao bound allows us to address[26] the following questions:

- How can a system designer trade capacity for noise immunity?
- How can a system designer trade bandwidth for capacity?
- How can a system designer trade additional receive sites against bandwidth?

<u>Capacity versus noise immunity.</u> The Cramér-Rao bound shows that doubling pulse duration compensates for doubling the noise and interference. However, doubling the pulse duration means only half as many pulses can be transmitted per second resulting in halving the number of location estimates per second.

<u>Capacity versus bandwidth.</u> Doubling the bandwidth quadruples the potential capacity, other system variables being kept the same.

<u>Bandwidth versus noise immunity.</u> The Cramér-Rao bound shows that doubling the bandwidth can compensate for a four-fold increase in noise power.

<u>Bandwidth versus accuracy</u>. The Cramér-Rao bound shows that doubling the bandwidth doubles the accuracy. We developed this intuitive relationship earlier as equation 2.

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[26] The Cramér-Rao bound only applies in situations where the time-of-arrival measurement system can operate more or less normally. If we increase the noise too much, this assumption fails. If we increase the system bandwidth too much, it becomes impossible to build a receiver using current technology. Nevertheless, in spite of these practical limitations, the Cramér-Rao bound is a good tool for studying tradeoffs. We know that we can do no better than predicted by the Cramér-Rao bound. The real world will always be worse than indicated in this analysis.

Power versus number of fixed sites. This is a more difficult issue to examine since the distance to the fixed sites does not appear directly in the Cramér-Rao bound. Assume the gird of fixed receiving stations shrinks with every fixed station moving closer to the mobile unit. Also assume that radio signals from the mobile unit to the base are attenuated in proportion to the fourth power of distance.[27] Under this propagation model, doubling the number of base stations in a city should compensate for a four-fold increase in interfering noise.

Accuracy versus number of fixed sites. Using the same model as in the preceding paragraph, we would predict that doubling the number of receive sites would, all other things being kept equal, roughly improve the accuracy by a factor of two.

[27] The fourth-power law is frequently used in mobile radio modeling. We use it here because it is roughly accurate and the exponent four makes the derivation easier to follow. Further, this assumption is conservative, in that slightly lower and more realistic values for a propagation exponent would make coping with interference more difficult.

VIII. Comparison of Teletrac's Performance with the Cramér-Rao Bound

Figure 5 below (a reproduction of Figure 11 in "Theoretical and Field Performance of Radiolocation Systems" by PacTel Teletrac) plots laboratory measurements made by Teletrac of the performance of the time-of-arrival estimation provided by the Teletrac base station receiver. The Teletrac system comes close to the Cramér-Rao bound. Notice that the performance shown in this graph parallels the Cramér-Rao bound but with an offset of about five dB. This offset represents the difference between an ideal time-of-arrival measurement system and the practical field implementation. As we will see later this five dB figure is small in comparison with the increase in the noise that would be created by operation of a cochannel pulse-ranging system. Consequently, better engineering of the Teletrac receiving system cannot protect against such interference. The laws of physics and statistics prevent this technical fix.

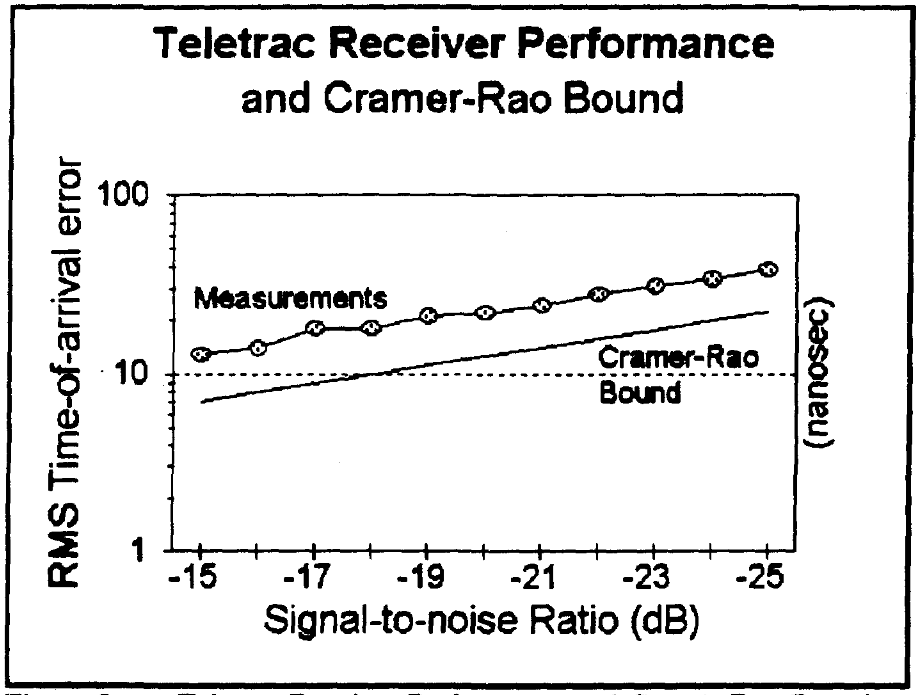

Figure 5 Teletrac Receiver Performance and Cramér-Rao Bound

Teletrac conducted extensive analytic studies of LMS service coverage and quality. Teletrac has also experimentally verified the predictions of the analytic models.

Teletrac's analytic and experimental results are summarized in Teletrac's study: "Theoretical and Field Performance of Radiolocation Systems." Upon examination, the analytic and experimental results reported in that study appear reasonable. The occasional divergences between the analytic and experimental results are to be expected for land mobile radio propagation modelling -- particularly with models such as Teletrac's which do not compute the effects of topography. Figure 1 of the Teletrac study shows a partial map of the predicted coverage of Teletrac's existing system in Dallas-Fort Worth, Texas. Figure 2 shows the predicted coverage in the presence of a single moderately powered interference source mounted on a high tower in the eastern side of the service region. Teletrac's field measurements in Dallas-Fort Worth confirmed this predicted loss of coverage.

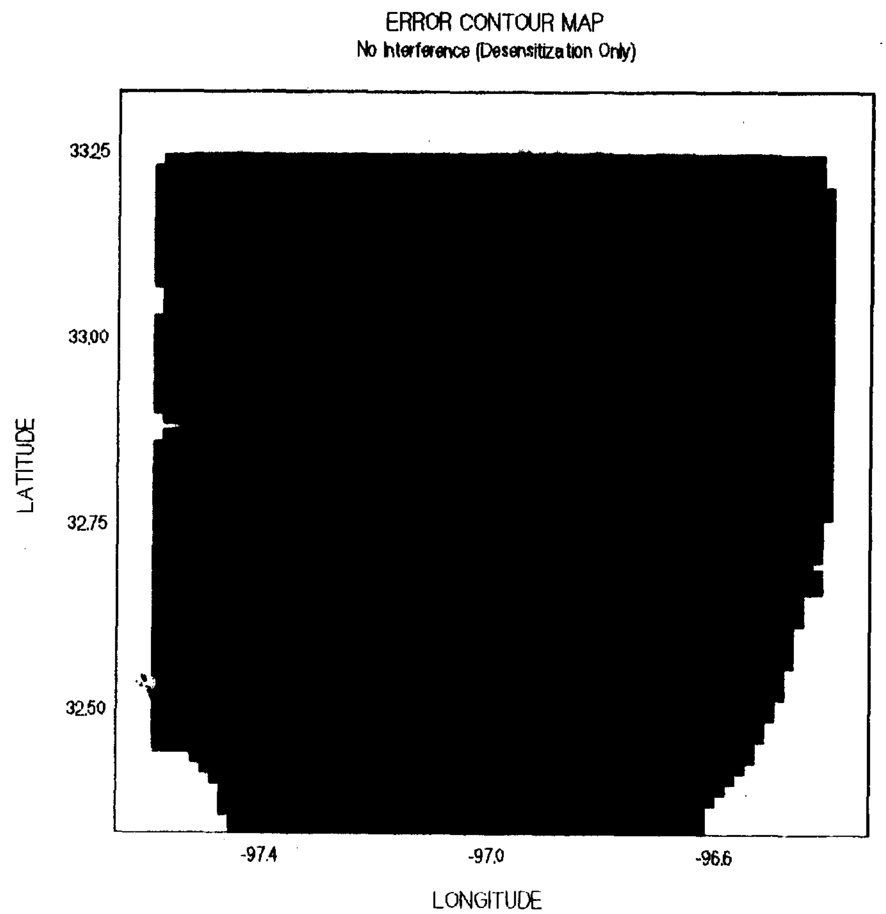

FIGURE 1 Pactel Teletrac Coverage without Interference

Figure 6 Figure 1 of "Teletrac Study"

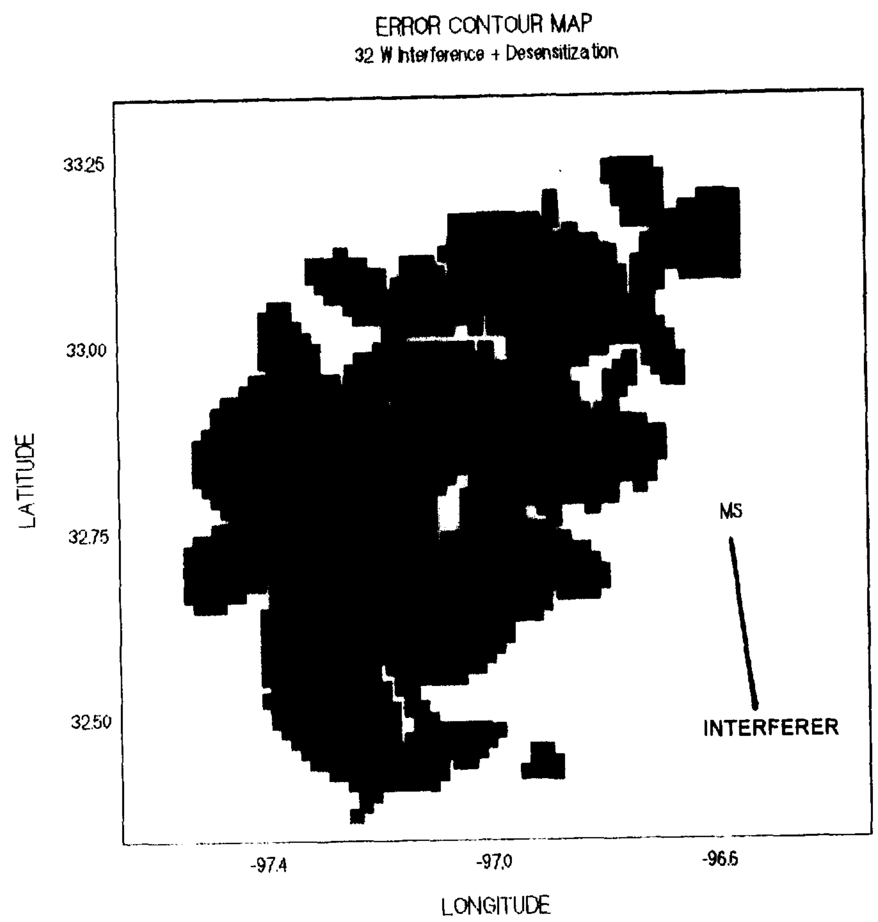

FIGURE 2 Pactel Teletrac Coverage in Presence of Interference

Figure 7 Figure 2 of "Teletrac Study"

The Teletrac experiments and analysis show that an LMS system that can function acceptably well in the 902-928 MHz band sharing environment will fail in the presence of interference from a cochannel LMS base station.

IX. Remedying Harmful Interference Between Wideband Pulse-Ranging Systems

What technological tools or techniques does society have to avoid the costs created by interference between pulse-ranging systems? We have identified eight primary methods to reduce or avoid such interference:

- use time-division techniques to separate the signals of collocated systems,
- use frequency division techniques or quasi-orthagonal sequences,
- use a higher power pulse,
- transmit a longer pulse,
- use additional bandwidth,

on odd-numbered seconds. This approach avoids the problem of fatal interference caused by high-power transmissions from one system into another. But, it presents a host of difficult issues that must be faced before time-division can be adopted. We consider four major issues below:

- defining rules,
- technical concerns,
- incentive issues, and
- the FCC enforcement burden.

Finally, we offer our conclusions.

1. Defining Time-Division Multiplexing Rules

Although it might appear easy to define workable rules for a time-division based band sharing, we believe that this is not the case. Consider a few alternatives. The most obvious approach is to use a listen-before-talking or carrier-sense multiple access (CSMA) approach. Such protocols are widely used on shared Part 90 channels and the Commission is well aware of the problems with equitable operation under such protocols. The FCC's Air-Ground telephone service also operates under such rules. Carrier sense techniques face a fundamental problem in the location and monitoring service because the flight time of a pulse across a metro area can be a significant fraction of the entire pulse duration.[29]

Another approach would be to schedule transmissions. Firm A could transmit for one second, Firm B during the next second, Firm C in the third second, and so on in a round-robin fashion. This approach avoids the problems associated with the carrier-sense approach, but brings problems of its own. Technical concerns include

[29] If we assume that the urban service area has a radius of about 30 miles (roughly Rockville to Lorton), then a radio pulse takes 0.16 milliseconds to cross the region. Yet, Pinpoint has proposed an LMS system that would use signalling elements only about five times longer than this.

synchronization and calibration overheads, coexistence with asynchronous terminals, and supporting low-power, long-pulse mobile units. These concerns are discussed in more detail below. This approach also has the disadvantage that, unlike a carrier sense approach, if Firm A needs the channel and Firm B does not, the channel still may sit idle during part of Firm B's timeslot.

A third approach would be to use a token-passing scheme to share the channel. Conceptually, the system operator with permission to be on the air would hold a token. After the operator's turn expired (either because the operator had completed all its scheduled transmissions or the maximum holding time had been reached), the operator would pass the token on to the next operator in line.[30] That operator would then begin transmissions until either all existing location requests had been satisfied or time had run out. Then the second operator would pass on the token. Although this approach allows for more efficient spectrum utilization than would straightforward time-slot sharing, it still poses many difficult technical problems.[31]

A fourth approach would be to assume the existence of a central control site in each city that would coordinate the spectrum access by the individual systems. In essence, this approach partially integrates all the separate systems into a single full system.

A fifth approach would be for the FCC to issue general hortatory language requiring cochannel licensees to share on an equitable basis but leaving it up to the licensees to work out the details. This approach minimizes the labor for the Commission in the drafting mode, but it leaves great uncertainty on down the road.

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[30] Of course, the token would be passed using an electronic signal. Local area networks using token-ring technology are in widespread use today.

[31] We are not aware of any radio-based system that uses such token-passing for channel sharing. We would expect that token-passing systems would be subject to failure modes due to occasional loss of the token due to noise and interference.

2. Technical Concerns with Time-Division Multiplexing

Any time-division multiplexing scheme runs up against some fundamental technological problems. First, LMS systems need to use some overhead transmissions to synchronize and calibrate their systems. Unless the systems are virtually identical, these overhead functions cannot be shared. Consequently, time-division sharing will require duplication of such overhead functions and waste of spectrum. Additionally, if an LMS system has a maximum time it can go without transmissions (e.g., limits on how long the various subsystems can operate in a open-loop mode) then, as additional firms are authorized in the band, time-division sharing will force the system across this limit. At best, overhead transmissions will increase at this point. At worst, the system will begin to fail.

Second, some LMS services may require rapid response by the system to customer actions. For example, when a motorist pushes a button requesting roadside aid or signalling an emergency, he or she would like to see a system acknowledgement in half a second, not ten seconds. Time-division multiplexing would necessarily degrade such services. More generally, time-division would not allow an efficient tradeoff between applications requiring different performance characteristics. For example, one LMS system might be delivering routine messages to an idle package delivery truck, while an important countermeasure to one approach to foiling the use of LMS systems to track stolen vehicles.

Fourth, time-division approaches would prevent the use of very long-duration, low-power pulses which would be used with small, battery-powered covert transponders for theft detection or other law-enforcement purposes. Teletrac informs us that their service has been used by several law enforcement agencies in a variety of enforcement activities. Some of these have involved battery powered covert tags. Technological options which permit longer battery life and smaller, more easily hidden transponders will have significant potential to aid crime prevention and law-enforcement.

3. Incentive Issues in Time-Division Sharing

Time-division sharing creates unfortunate incentives. For two separate LMS systems to time share a band in the same region it is, by definition, necessary that each firm has built a stand-alone system capable of serving its region on a full-time basis. Consequently, a firm can expand its output at zero marginal cost. The only problem with expanding output is that it runs into the time-shares allocated to other firms. Consider a city with two firms, A and B, operating LMS systems in the band 904-912 MHz. Under one reasonable sharing policy they each get 50 percent of the time available.[33] Suppose that business is going well and firm A needs more capacity. One way to get more capacity would be to go back and reengineer its system. Another way would be for A to set up a "new" entrant, call it A-prime, who would enter the market. Now the market would have three firms, A, A-prime, and B. Under our assumed reasonable sharing policy they would each get one third of the capacity of the band. A-prime could save a lot of money if it rented capacity from A instead of building its own system. Given the technology and the rules, A and B each have an enormous incentive to create such additional firms to get an additional spectrum share and to deny capacity

[33] Subject, of course, to any overhead losses.